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Investigation of the $^{37}\text{Ar}(n,p)^{37}\text{Cl}$, $^{37}\text{Ar}(n,\alpha)^{34}\text{S}$ and $^{39}\text{Ar}(n,\alpha)^{36}\text{S}$ reactions at various stellar temperatures

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A first experimental study of the neutron induced charged particle reactions on ^{37}Ar and ^{39}Ar as a function of the neutron energy has been made. Therefore, complementary measurements were performed with thermal neutrons at the High Flux Reactor of the ILL (Grenoble, France) and with resonance neutrons at the GELINA neutron spectrometer of the IRMM (Geel, Belgium). The stellar cross sections, which were calculated from the obtained data, show important discrepancies with the theoretical values used in recent network calculations.

1. INTRODUCTION

Although the bulk of the elements between Si and Fe is considered to be created during the hydrostatic and explosive burning stages in massive stars, an investigation of the s-process path in this mass region is interesting for several reasons.

There are a few (neutron-rich) isotopes like ^{36}S and ^{40}Ar which are bypassed by the charged particle reactions and for which origin the weak component of the s-process is regarded as a possible scenario [1–3]. Also the radioactive species ^{40}K ($T_{1/2} = 1.28 \text{ Gy}$) seems to be created in this environment. Once the origin of ^{40}K could be established, its calculated abundance will serve as a constraint for calculations of nuclear cosmochronology. For all three isotopes mentioned, the branching at ^{39}Ar plays a key role because it determines the mass flow coming from the ^{36}Ar and ^{38}Ar seeds. To a lesser extent, also the ^{37}Ar branching comes into play at this point.

The s-process branching at ^{37}Ar is also of importance in the interpretation of recent observations of non-solar $^{35}\text{Cl}/^{37}\text{Cl}$ isotopic ratio in the circumstellar envelope IRC+10216 of CW-Leo [4]. The reliability of the AGB stellar model used for this analysis also depends on the stellar cross section data for the involved reactions. Since ^{37}Cl is directly produced

via $^{37}\text{Ar}(n,p)$, the latter is one of the key reactions in this respect.

So far, only theoretically calculated values were available for neutron induced reactions on ^{37}Ar and ^{39}Ar , the main reason being the unavailability of suited samples. Since the reliability of statistical calculations in this mass region is rather poor, certainly with the proximity of a closed neutron shell ($N=20$), we wanted to provide experimental cross section data for both Ar isotopes.

2. EXPERIMENTAL TECHNIQUE, ANALYSIS AND RESULTS

2.1. Description of the Argon targets

A crucial step in performing a reliable cross section measurement is the production and characterisation of suited samples. In this case several problems had to be tackled. Both ^{37}Ar ($T_{1/2}=35\text{d}$) and ^{39}Ar ($T_{1/2}=269\text{a}$) are gaseous, unstable and commercially not available. Moreover, the samples were intended to be used with surface barrier detectors as well as with ionisation chambers. Therefore an implantation in an Al foil seemed the most appropriate solution.

For the case of ^{37}Ar this was done at the UCL (Louvain-la-Neuve, Belgium), where ^{37}Ar atoms were produced via the $^{37}\text{Cl}(p,n)^{37}\text{Ar}$ reaction by bombardement of a compressed NaCl target with a 30 MeV proton beam. After ionisation and subsequent magnetic separation the ^{37}Ar atoms were implanted at 20 keV in a 20 μm thick Al-foil. Due to the short ^{37}Ar half life, a new sample had to be produced for every experimental campaign (Section 2.2). In this way samples containing up to 7×10^{15} ^{37}Ar atoms were produced.

The ^{39}Ar sample was produced at the ISOLDE facility at CERN (Geneva, Switzerland) via spallation of a TiO target. Here, the ^{39}Ar atoms, after ionisation and magnetic separation, were implanted at 60 keV in a 12 μm thick Al foil. After a first test implantation, the use of an optimized setup resulted in a sample containing 3.2×10^{14} ^{39}Ar atoms.

The number of atoms contained in the various samples, both for ^{37}Ar and ^{39}Ar , was determined at the IRMM (Geel, Belgium) via the detection of their radioactive decay products.

2.2. Measurements

2.2.1. Thermal neutrons

A precise determination of the thermal cross section value is of great interest for several reasons. Apart from the pure nuclear physics point of view, the thermal cross section is often used as a normalization point for measurements at higher energies and it also occurs in the calculation of the Maxwellian Averaged Cross Section (MACS) as a sum of its $1/v$ extrapolation to higher energies and the contributions of the resonances.

The measurements, which are ongoing for the $^{39}\text{Ar}(n,\alpha)$ case, are performed at the High Flux Reactor of the ILL (Grenoble, France). There, an intense (3.5×10^8 n/cm²s) and well thermalised neutron beam is available. Our experimental setup consists of a vacuum chamber in which the sample is mounted together with suited surface barrier detectors (according to the particles to be observed) which are placed outside the neutron beam.

The measurements on ^{37}Ar resulted in precise cross section values for the (n,p) (37 ± 4 b) and (n,α_0) (1070 ± 80 b) transitions. Moreover, the (n,α_1) and $(n,\gamma a)$ transitions were observed with cross sections of (310 ± 100 mb) and (9 ± 3 b) respectively [5].

For the ^{39}Ar case, the preliminary data permit the determination of an upper limit of

Figure 1. The $^{37}\text{Ar}(n,\alpha)^{34}\text{S}$ cross section from 10 meV up to 10 keV.

100 mb for the thermal cross section.

2.2.2. Resonance neutrons

The measurements with resonance neutrons on ^{37}Ar were performed at the GELINA pulsed neutron source of the IRMM (Geel, Belgium) using a flight path of only 9 m long. The choice for the shortest flight path available was totally determined by the limited amount of sample material.

The neutron energy range from 10 meV up to 100 keV was covered in three experimental campaigns. In a first campaign the linac was operated at 100 Hz in order to study the energy region below 1 eV. The region between 1 eV and 10 keV was covered by increasing the linac frequency to 800 Hz. In this measurement the region above 10 keV was blinded by the γ -flash, the prompt γ -radiation which accompanies the neutron production. In order to extend the energy range, the hindrance of the γ -flash was reduced by replacing the classical Frisch gridded Ionisation Chamber (FIC) by a Compensated Ionisation Chamber (CIC) [6].

Our effort made clear that the $^{37}\text{Ar}(n,\alpha)$ cross section is characterized by a $1/v$ shape up to approximately 100 eV, confirming the thermal value obtained at the ILL, and by two prominent resonances in the keV region, as can be seen in Fig. 1. The latter were analysed with the R-matrix fitting code SAMMY, which enabled a determination of the partial level widths [6].

3. STELLAR CROSS SECTIONS AND DISCUSSION

For the $^{37}\text{Ar}(n,\alpha)^{34}\text{S}$ reaction the obtained cross section data were used to calculate the Maxwellian averaged cross section via integration over the data. As no (n,p) transitions were detected, the corresponding MACS was calculated by combining the thermal value obtained at Grenoble and the resonance parameters determined in the analysis of the $^{37}\text{Ar}(n,\alpha)^{34}\text{S}$ data. In Fig. 2 we compare our values with the statistical model calculations by Woosley et al. [7], which were used in network calculations up to now. MACS values

Figure 2. The $^{37}\text{Ar}(n,\alpha)^{34}\text{Ar}$ (left) and $^{37}\text{Ar}(n,p)^{37}\text{Cl}$ (right) Maxwellian averaged cross sections. The present data are compared with two different theoretical calculations.

obtained with the Hauser-Feshbach codes NON-SMOKER [8] and MOST [9] are also shown. Large discrepancies appear between the experimentally and theoretically obtained values.

A $1/v$ extrapolation of the upper limit for the $^{39}\text{Ar}(n_{th},\alpha)$ cross section can be regarded as a first estimate for the corresponding MACS. This bold extrapolation results in quite lower values compared to the theoretical ones. Differences with the Woosley values of a factor 40 and 35 at 8 and 30 keV respectively are obtained.

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